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An integrated assessment of location-dependent scaling for microalgae biofuel production facilities

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A B S T R A C T

Successful development of a large-scale microalgae-based biofuels industry requires comprehensive analysis and understanding of the feedstock supply chain—from facility siting and design through processing and upgrading of the feedstock to a fuel product. The evolution from pilot-scale production facilities to energy-scale operations presents many multi-disciplinary challenges, including a sustainable supply of water and nutrients, operational and infrastructure logistics, and economic competitiveness with petroleum-based fuels. These challenges are partially addressed by applying the Integrated Assessment Framework (IAF) – an integrated multi-scale modeling, analysis, and data management suite – to address key issues in developing and operating an open-pond microalgae production facility. This is done by analyzing how variability and uncertainty over space and through time affect feedstock production rates, and determining the site-specific "optimum" facility scale to minimize capital and operational expenses. This approach explicitly and systematically assesses the interdependence of biofuel production potential, associated resource requirements, and production system design trade-offs. To provide a baseline analysis, the IAF was applied to a set of sites in the southeastern U.S. with the potential to cumulatively produce 5 billion gallons per year. The results indicate costs can be reduced by scaling downstream processing capabilities to fit site-specific growing conditions, available and economically viable resources, and specific microalgal strains.

1. Introduction

The global demand for energy is projected to increase 26% by the year 2035 because of emerging economies and population growth centers [1]. The demand for liquid transportation fuels is expected to increase the most among energy sectors, placing more pressure on conventional and unconventional petroleum-based fuels. This demand makes it more likely that balance-of-trade issues in the global market will lead to price instabilities, supply interruptions, and more challenges to national security (both direct and indirect) [2]. Chu and Majumdar [3] call for a new industrial revolution where sources of energy are affordable, accessible, and sustainable. They point to alternative energy innovations that can displace conventional sources and make the energy system more robust through greater diversity of energy sources.

One alternative liquid transportation fuel is sourced from photoautotrophic microalgae, where high fuel yields per unit area of land can be achieved using existing/waste sources of CO_2 and a range of water types and sources. Microalgae can be used in many different fuel conversion pathways, such that they can be tailored to produce a variety of drop-in fuels. A large body of research surrounds microalgae production—from microbiology and bioinformatics to system operations and life-cycle analysis to social impacts and policy. All of this research seeks to understand the potential viability and sustainability of a microalgae-based biofuels industry in terms of resource-use, feedstock demand, net energy production, system benefits, and economics.

Developing a large energy-scale microalgae-based biofuels industry requires a comprehensive analysis and understanding of the feedstock supply chain, including 1) facility siting and design; 2) resource requirements, availability, and recycling; 3) strain selection and methods of

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growth; 4) harvesting and dewatering; 5) transport logistics; and 6) upgrading the feedstock to different fuel pathways. Such analyses, many of which are addressed in this paper, are required to evaluate 1) the specific site conditions such as suitable land availability and cost; 2) local meteorology and climate considering multi-scale temporal trends and variability that affect feedstock growth; 3) available resources such as water, CO_2, power, transportation infrastructure, and the costs and logistics associated with each required resource; 4) the best performing microalgae strains for the climate, water chemistry, and ultimate fuel conversion pathway; and 5) the site design and function, including the methods of cultivation, harvesting, dewatering, extraction, nutrient and water recycling, blowdown requirements, net energetics, and economics of the operation.

Evaluation of these factors in microalgal biofuel enterprise design requires explicit consideration of spatial and temporal variability in feedstock production as a function of the local weather variability on hourly, daily, seasonal, annual, and even decadal time scales. The evolution from pilot- to energy-scale operations presents many multi-disciplinary challenges beyond microbiology and chemical engineering, including identifying and establishing sustainable resource supplies, operational and infrastructure logistics, and process engineering, all of which drive toward economic competitiveness with petroleum-based fuels [4–10].

This study describes and demonstrates a new modeling capability – the Integrated Assessment Framework (IAF) – that directly integrates spatiotemporal-based resource analysis with techno-economic analysis (TEA) capabilities in a high-performance environment. This integration provides the ability to 1) assess variability and uncertainty in unit area biomass production over time and space; and 2) evaluate the effects of site-specific facility scaling on capital and operational expenses. This study also demonstrates the mutual benefit and modeling advancements that come from integrating a suite of resource assessment models with a techno-economic model.

1.1. Resource assessment

A major research area defined by the US DOE and the National Resource Council regards further understanding of resources around microalgae biofuel production potential and requirements to support sustainable production [5,11]. This notion is not new, however, as resource assessments were conducted under the US DOE Aquatic Species Program (1978–1996) in order to understand the possible future and viability of microalgal-based biofuel production in the United States [5,12–15]. Maxwell and Folger [12] stressed the intrinsic interconnection between available natural resources, environmental conditions, and the future success and sustainability of aquatic biomass production systems. Resource assessment includes the resource potential (e.g., biomass/lipid production rates and quantity of production per unit time and area), the resource demand (e.g., suitable land area; water type, quality, source, supply, and transport; availability and transport of nutrients and CO2; soils and geology; and existing competition for resources), and the risks that impact the resource supply or demand (e.g., droughts, floods, earthquakes, infrastructure availability, supply disruptions, temporal availability). Many prior studies established and demonstrated resource assessment from which this research is directly or indirectly built upon [8–10,12–21]. Resource assessment used in concert with TEA helps to identify the most probable and sustainable locations for microalgae production facility development using the best available knowledge of resources, as described above, and the economics driving required resource supplies, production, and product delivery.

1.2. Techno-economic analysis

TEA is a valuable approach for identifying and understanding key cost and subsequent technology constraints that potentially affect the commercialization and success of a microalgae biofuel industry. TEA is effective for modeling the process design, performance, and resulting costs, as individual components of a facility or enterprise, thus enabling a measure of performance relative to cost among various technologies and design scenarios. However, as noted by Pienkos et al., [22] TEA is a conceptual process to understand how system designs impact performance and costs. An increasing number of TEA studies have addressed the feasibility of commercial microalgae production with different cultivation and process designs, harvesting, dewatering, conversion pathways, and assumptions [6–8,16,23–30].

For the TEA studies that compared the economics of an open pond to a photobioreactor system, the open pond systems were significantly less expensive and growth rate and lipid content were the major drivers for improved economics. However, as noted by a joint model and parameter harmonization study by Argonne National Laboratory (ANL), the National Renewable Energy Laboratory (NREL), and Pacific Northwest National Laboratory (PNNL) [8], increased productivity yields and lipid content alone would not lower costs to the point of being cost-competitive with petroleum fuels and meeting established greenhouse gas targets. This suggests the need to inspect engineering and operational details [25], including site and process engineering (e.g., pond liners, soil compaction and plugging, system energy and resource efficiencies) and evaluate the use of different algal strains at different locations and for different seasons of the year [16,21].

The variability of algal biomass production over space is well represented in Wigmosta et al. [18], Quinn et al. [19], and ANL/NREL/PNNL [8] and represents dominant production factors of light and temperature; however, these studies place less emphasis on production variability over time. A majority of the referenced TEA studies are set up and demonstrated at a single location, limited geographic domain, or use broad generalizations to represent large geographic areas. Additionally, many of these studies use a time-invariant steady-state production condition or mean annual production value and neglect production variability driven by environmental forcings over time. However, the literature emphasizes the importance of spatially and temporally explicit calculations of biomass production and its intrinsic linkage to production cost [6–8,16,19,29].

1.3. Scaling

The notion of scaling plays a central role in production theory and is critical in most industries where an understanding of how the economies or diseconomies of scale and diminishing returns affect the cost of the product being produced. The ideal efficiency determines, among the many variables in an operation, when the minimal cost of unit inputs provides the maximum amount of unit financial return. Additional factors beyond input costs and output gains, including environmental, social, and policy needs, must also be evaluated.

Within the energy sector, effective scaling approaches have been applied in the petroleum and power generation industries [31,32], and a large body of work has ensued for the terrestrial biofuels industry [33–36]. Experience within these other industries suggests that with each feedstock/strain, harvesting, processing, and conversion pathway, a unique combination of process specific unit scaling, which culminates to the overall facility, identifies an ideal site-specific biomass production capacity which drives toward efficiencies and optimal gains. In addition, the influence of time (i.e., duration and magnitude of feedstock supply rates) and space (i.e., geographic distribution and quantity of production and processing facilities) has been demonstrated to be variable and suggests there may also be an impact on scaling [6–10,16,19,21,29].

The ideal scaling of an open pond microalgae production facility depends on the type or strain of microalgae grown; the media type; pond depth; nutrient application; mixing; the process used for harvesting, dewatering, and recycling of water and nutrients; and the fuel conversion pathway. The site location strongly influences the timing of biomass production and access to required resources (i.e., water), particularly at the peak production season when resource demand and competition are high. Duration curves are used in the IAF to address production and downstream process scaling for unique sets of design operations, allowing for trade-off analysis among algal strains, production and process designs, fuel conversion pathways, water sources, and other required resources.

2. Model and methodology

To help address factors of space, time, and scale systematically, consistently, and efficiently, and within the context of microalgae production, we developed the Integrated Assessment Framework—a unique modeling capability comprised of a suite of tightly coupled prediction, analysis, and assessment components. The IAF provides a flexible analytical and data management environment that enables site, regional, and national assessments of potential microalgae production capabilities and feedstock supply chain logistics. It is designed to systematically assess the interdependence of biofuel production potential, associated resource requirements, and production system design trade-offs (e.g., components and/or throughput capacity).

Key issues related to developing and operating an open-pond microalgae production facility are addressed in the IAF, focusing on the variability and uncertainty in production at a given site and evaluating how facility scale affects capital and operational expenses. Capabilities within the IAF are implemented by applying spatial, temporal, and operational rigor in a techno-economic style analysis to identify trade-offs and cost-effective operations for microalgae production. This assessment process involves analysis of multiple combinations of algal feedstock production requirements, including 1) algal strain; 2) required land area; 3) water type and quantity; 4) source and quantity of nutrients and CO_2; and 5) production system capacities and designs. For example, evaluating trade-offs to determine an optimum processing system design capacity as a function of location and algal strain requires the analysis of thousands of combinations to be realized. Hence, the requirement for a robust modeling system founded on advanced software design principles, thus enabling these scenarios to be realized in a high-performance distributed computing environment.

The IAF was created by integrating a number of existing and new modeling/analysis components. Individual model and analysis capabilities of the Pacific Northwest National Laboratory's Biomass Assessment Tool (BAT) [9,18,20] are coupled to the system dynamics and techno-economics of Idaho National Laboratory's Algae Logistics Model (ALM) [37], and a newly developed framework manages the flow of parameters and data between models, providing a data management system to administer, execute, store, and retrieve scenarios. The IAF is adaptive and is designed to incorporate new feedstock production, harvest, and processing technologies and design parameters that evolve with advances in research.

The following sections describe the elements comprising the IAF. Sections 2.1 and 2.2 briefly describe the BAT modeling framework and ALM, respectively. Section 2.3 provides an in-depth description of the IAF and how it incorporates the BAT and ALM tools with new investigative capabilities developed to help determine an ideal design scale for open-pond production sites, while explicitly considering the effects of time and space. Finally, Section 2.4 discusses the development and use of duration curves for design scaling.

2.1. Biomass Assessment Tool

The BAT is an integrated model, analysis, and data management research and development architecture that couples advanced spatial and numerical models to capture site specific environmental conditions, production potential, resource requirements, and sustainability metrics for bioenergy feedstocks. Various aspects of the BAT have been described and demonstrated in a number of published studies [8–10,18,20] in addition to being used in private industry where results have helped answer key business questions. This technology continually evolves to meet new research questions, approaches, and developed models; for this reason, the BAT system was designed to be modular, allowing for new components to be developed and linked in, thus allowing access to and use of existing data repositories and models to build up required analysis scenarios.

At a high-level, the BAT incorporates 1) multi-scale modeling, 2) physics- and biophysical-based modeling, 3) least-cost modeling, 4) resource demand, 5) economics, and 6) other analyses performed using the best and most currently available climate, water, land, and infrastructure data, along with environmental constraints, biomass growth rates, and other resource requirements, such as nutrient and CO_2 sources. At a more detailed level, the system includes 1) a multi-scale land-suitability model, 2) an open and closed mass and energy balance pond model, and 3) a biomass growth model with a growing library of algal strain parameters, 4) trade-off analysis routines to evaluate biomass production potential with available land and water resources, 5) water source and use intensity analysis under current and altered climates for freshwater, seawater, and saline groundwater, 6) nutrient and CO_2 flue gas source, availability, and demand models, 7) least-cost transport models for water, nutrients, CO_2, and refinery access, 8) a land valuation/acquisition model, and 9) a site leveling model (Fig. 1).

The BAT operates at a high spatiotemporal resolution (e.g., 30–500 m depending on the dataset, hourly) within the conterminous United States. Some capabilities within the BAT were recently expanded to the global domain using medium-scale spatial resolution (e.g., 1–20 km depending on the dataset) while maintaining a high temporal frequency (e.g., 3-hourly), thus capturing important diurnal effects. The BAT is adaptive and scalable and is designed to communicate with other external models such as the ALM. Model inputs and run results are transferred to an intranet-based relational database using web protocols.

2.2. Algae Logistics Model

The ALM is a modeling system that drives TEA using a systems dynamics approach and incorporates modular system and technology components. These components are dynamically linked together to provide a facility design configuration that can be tested for a range of user-defined parameters [37–39]. For example, different dewatering technologies can be plugged into the modeled process stream and tested for their individual and system-wide sensitivities on capacity, throughput, energy use, and economics by way of capital expense (CapEx) and operational expense (OpEx). The model framework, system, and many of the databases are derived from an earlier and ongoing effort, the Biomass Logistics Model (BLM), which focuses on terrestrial biomass feedstocks and its respective supply systems [40].

The ALM was designed and built to represent an open-pond microalgae production facility using aggregated hourly data to run at a daily time step and includes external resource inputs in terms of quantities and costs for delivery, e.g., water, nutrients, and system processes representing cultivation, harvest, dewatering, extraction, fuel upgrading, and resource recycling. CapEx is established from land value and site preparation costs [20] and internal equipment, labor, and operations databases taken from public and industry sources [37]. The customizable and interchangeable modules enable future dynamic design and analysis of alternative algae supply chain systems starting at the site scale and expanding to local-, regional-, and/or national-scale enterprises. The ALM modules are developed using the commercial system dynamics software package Powersim™, which provides the operational design, linkage, simulation, energetics and cost accounting.

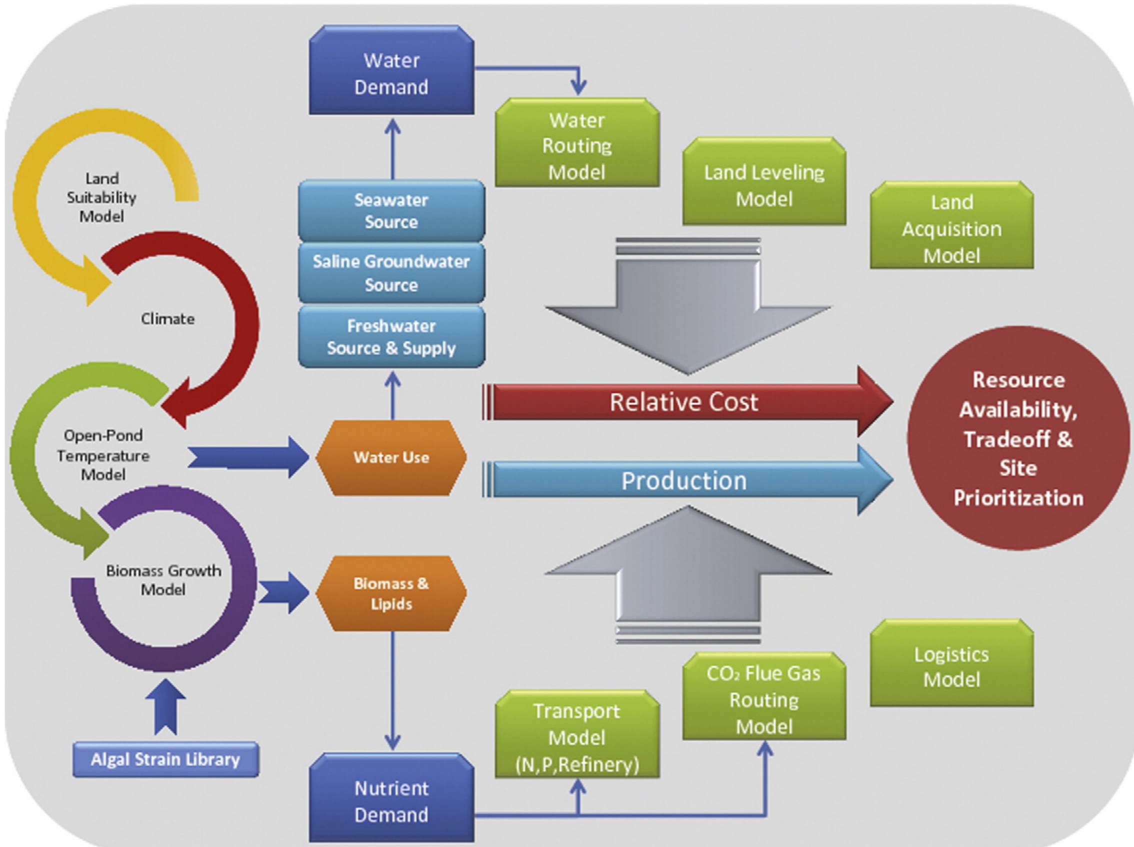

Fig. 1. The Biomass Assessment Tool (BAT) is an integrated model, analysis, and data management architecture that couples advanced spatial and numerical models to capture potential site environmental conditions, production potential, resource requirements, and sustainability metrics for bioenergy feedstocks.

2.3. The Integrated Assessment Framework

The IAF can explicitly and efficiently assess a multitude of algal biofuel production design configurations over time and space for thousands of individual sites, thus enabling the exploration of trade-offs between site-specific production potential, resource constraints, and processing capacity using a long-term record of meteorological conditions. Alternative scenarios can then be systematically and

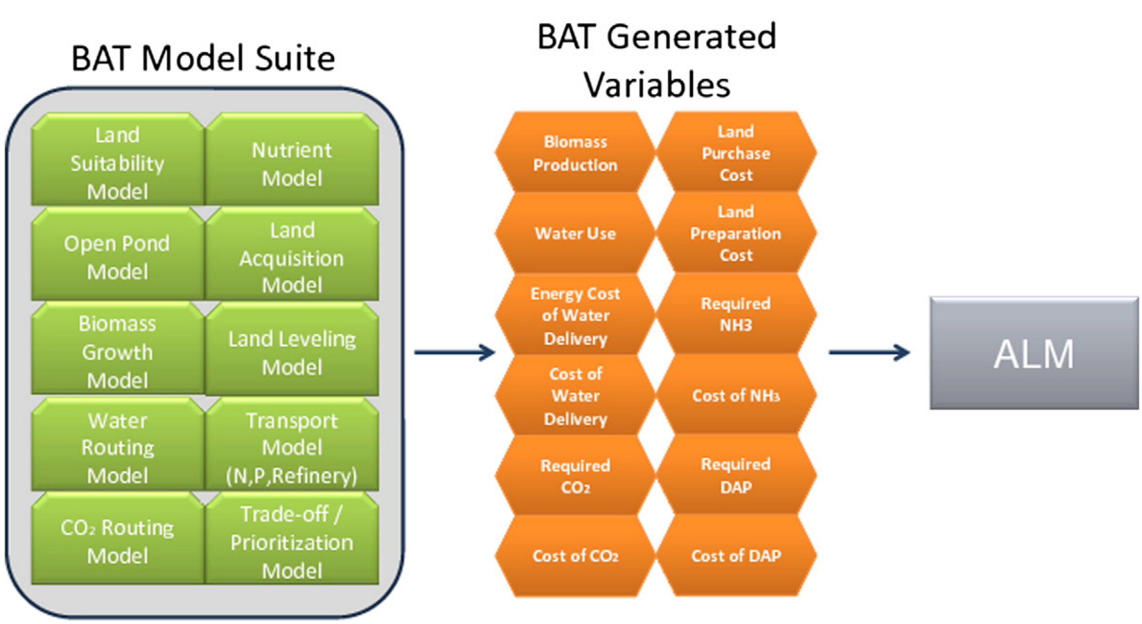

Fig. 2. Several modules within the Biomass Assessment Tool (BAT) supply required variables to the Algae Logistics Model (ALM) for individual locations around the U.S.

automatically evaluated to determine the optimal logistics combinations for a given site, region, or nation, or alternatively to achieve a prescribed production target. The IAF brings to bear site-specific biomass production, technology pathways, and associated costs for any location in the United States. In addition, by providing location-specific inputs to the IAF cost database, the IAF can be run for any location in the world.

The ALM is run with a specified production design scenario, and all potential sites are simulated to assess parameters such as total operating days, harvest days, pond operations (energetics), total biomass and gallons of lipid produced, itemized CapEx, OpEx, and dollars per gallon of produced renewable diesel. These results are delivered to the BAT database for data reduction and analysis, including production cost curves, site sub-selection, clustering of sites, and visualization. The interactions between the BAT and ALM are handled through a web-based communication layer that receives run parameters and spatially and temporally explicit data inputs from the BAT, executes the appropriate modules within PowerSim, and delivers the resulting data to the BAT database (Fig. 2).

Incorporating modeling components from the BAT and ALM, along with other unique capabilities designed specifically for the framework, the IAF (Fig. 3) consists of: 1) a physics-based model of an open-pond system that balances mass and energy delivering hourly pond water temperature and evaporative water loss based on local weather data [18]; 2) a biophysical growth model that incorporates pond temperature, optimal/sub-optimal temperature curves, and photosynthetically active radiation to simulate strain-specific biomass growth, nutrient demand, and associated lipid content at an hourly time-step [8,10,18]; 3) a series of spatial models that determine potential suitability, availability, purchase and preparation costs of land; the source, transport energetics, delivery cost of water; and the source, availability, and cost of key nutrients including CO_2, N, and P [9,10,20]; 4) a dynamic and modular logistics model that considers the feedstock supply chain system, including logistics, costing, performance, and feasibility, and provides a TEA of site-specific facility production costs, including energetics, capital investment, and operating expenses [13]; 5) an optional component to define site-specific operational windows based on minimum daily biomass productivity and duration of productivity; 6) an optional component to exercise dynamic pond harvesting as well as continuous harvesting and mass accounting when pond culture densities reach a user-specified target; and 7) a process component that builds production duration curves based on modeled long-term performance to assess “optimal” design and operating capacities at individual sites. The core capabilities within the BAT are founded on the performance of the pond temperature and growth models. The mass and energy balance of the pond temperature model was initially validated against observed evaporative water loss data in different hydroclimatic zones throughout the U.S. [18] suggesting reasonable model skill. More recently, the pond temperature and growth model results were validated against 7-months of observed data in multiple depth ponds showing a mean average growth difference of 0.6 g/m^2day and a pond temperature difference of 1.6 °C. These models have been reviewed by and are being used in industry.

The IAF offers several unique capabilities compared with previous efforts demonstrated in the literature, including 1) tight-coupling and

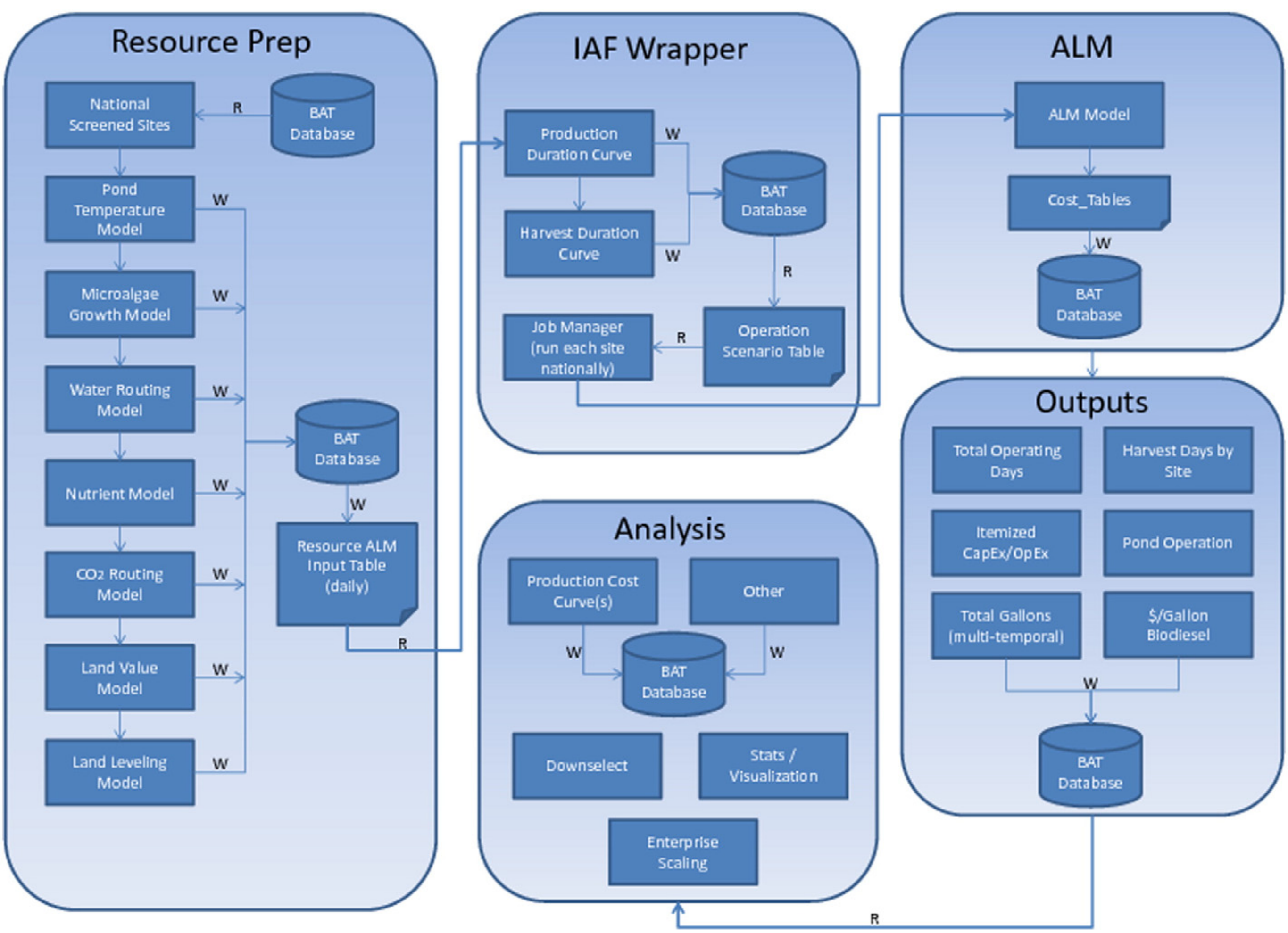

Fig. 3. The general architecture and workflow of the Integrated Assessment Framework (IAF) comprise data retrieval, passing, and storage from the BAT to the ALM, enabling specific IAF functions to be run at each time-step. Results are stored in a scenario-specific table within the BAT database.

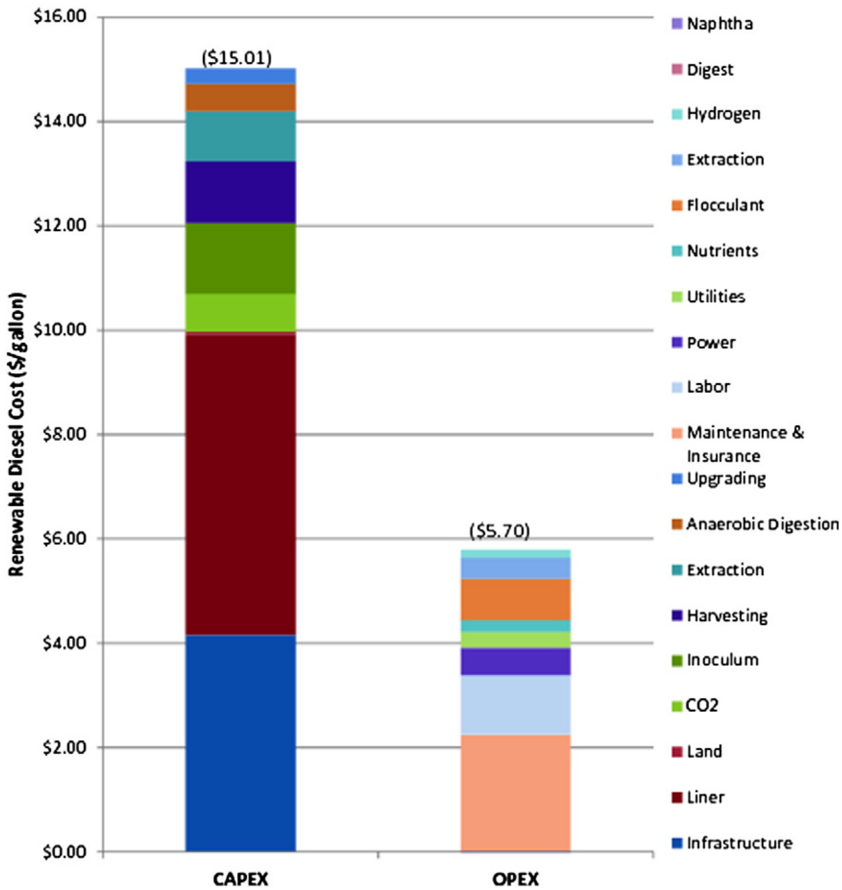

Fig. 4. ALM-generated CapEx and OpEx cost breakdown for a site in Beaumont, Texas.

automated resource assessment and techno-economic assessment models; 2) the inherent capability to process large amounts of data on multi-core and cluster/supercomputers, enabling site-specific analysis under multiple scenarios for tens of thousands of pre-screened or user-defined locations; 3) site-specific operational windows driven by a user-defined ruleset comprised of minimum production over a period of time; 4) user-defined dynamic pond harvesting; and 5) the development of production duration curves and TEA analysis at user-defined increments along the duration curve (again requiring large computing capability support).

The IAF currently only uses an open-pond production system for several reasons: 1) in the near-term, open-pond cultivation is more economically feasible according to the TEA studies cited above; 2) commercial operations for the nutraceutical, feed, cosmetic, and biofuels industries have demonstrated use with open ponds [41–44]; and 3) the approach requires less capital investment and operational expense and offers better energy efficiency, making it more viable at energy-scales [45–47].

2.4. Duration curves

Exceedence probabilities are used to evaluate variability in a system and help determine the likelihood of a value being equal to or less than another value within a given data series. The probability values, P, are expressed as the percentage of time in which the value will be exceeded. For example, P_{90} is a value that is exceeded 90% of the time; P_{50} would represent a mean condition, whereas P_{10} represents values that occur less frequently. Exceedence probabilities are represented in flow duration curves or cumulative frequency curves; they are a common design tool in hydrology and engineering and have been in use for nearly a century [48,49]. The flow duration curve uses a time series of flow data at a given time-step and sorts, ranks, and normalizes the flow to create a curve that does not consider the chronological order of events, but rather the overall flow characteristics, making it suitable for comparing individual locations.

The flow duration curve technique was adopted as an analytical tool to help inform TEA within the IAF. We developed the "production duration curve" to evaluate the "optimal" design capacity of a production facility to help scale the post-cultivation equipment in a user-configured facility. The production duration curve evaluates the hourly aggregated mean daily time series of total produced biomass as estimated by the biomass growth model and assumes harvest occurs once the pond reaches a user-defined culture density. The IAF calculates the duration curve using the entire time series, in this case, 30 years of hourly growth data aggregated to a daily value to capture long-term weekly, monthly, seasonal, and inter-annual growth conditions.

The calculation of the curves provides the amount of biomass available for harvest and downstream processing at the minimum, maximum, and user-specified percentage increments. Thus, for a given site running at 10% increments along the duration curve, 11 capacity design scenarios are run through the IAF. The objective is to produce a production cost curve that reveals the ideal design capacity, thus balancing the CapEx and OpEx of algal production at a given design capacity with the cost of feedstock harvest and conversion at alternative design capacities.

3. Case study

In 2011, the U.S. Department of Energy's (DOE's) Bioenergy Technologies Office began an initiative to harmonize resource assessment, TEA, and life-cycle analysis model parameters [8]. The intent was to establish a baseline assessment that represents not only a "plausible near-term production scenario" but also a point of departure from which

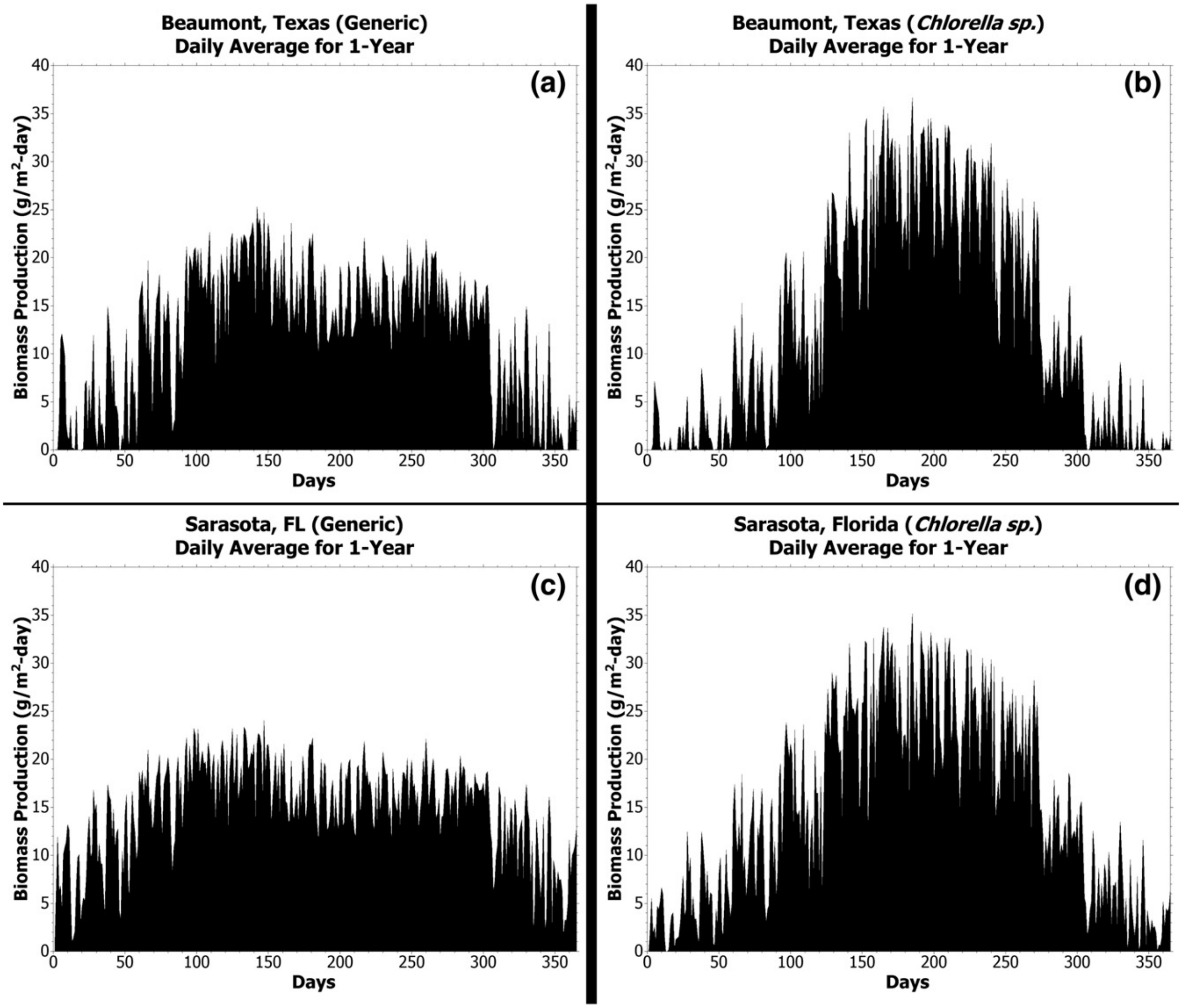

Fig. 5. Variability in average daily algal biomass productivity over a common 365-day sample period including (a) generic strain at Beaumont, Texas, (b) *Chlorella sp.* at Beaumont, Texas, (c) generic strain at Sarasota, Florida, and (d) *Chlorella sp.* at Sarasota, Florida.

additional future analysis and new technologies can be evaluated. A national analysis sub-selected the high-production areas of the southeastern and Gulf Coast regions of the United States, yielding a long-term annual total renewable diesel output of approximately 5 billion gallons per year (BGY). The study determined that increased productivity yields and lipid content alone would not lower costs to the point of being cost-competitive with conventional transportation fuels and meeting greenhouse gas targets, but scenarios were developed that show significant progress toward these objectives.

In concert with this effort, a baseline analysis and model validation were established within the IAF using the same harmonized set of parameters as the resource assessment and techno-economics, with several exceptions: 1) CO_2 was delivered at $40 per ton within the IAF instead of explicitly considering flue gas transport as in the harmonization effort [8]; 2) the unit farm was set to 405 ha of open pond instead of the harmonized 4050 ha area; 3) in addition to the original “generic microalgae” strain introduced by Wigmosta et al. [18], the algal strain, *Chlorella sp. 1412* (hereafter *Chlorella sp.*) was also incorporated; and 4) to emphasize the site specificity and the high computational performance of the IAF, 4,460 individual sites were modeled as opposed to using representative results from 8 regional clusters.

The sites considered in this case study are identical to those used in the harmonization study where freshwater demand and availability were used as a resource constraint to filter out sites from the original U.S. site selection of Wigmosta et al. [18]. From the sites with available freshwater, the study then identified the best-producing sites to accumulate 5 BGY of renewable diesel. The selected sites were primarily located in the Gulf of Mexico coastal region and on the Atlantic Coast of Florida.

For this case study, the unit farm was composed of 405 ha of lined open ponds and 80 ha of infrastructure and processing equipment. The microalgae growth model was run with strain-specific model parameters that reflect water temperature constraints, optimal temperature ranges for growth, light saturation, and lipid content. The algal biomass is assumed to be harvested and dewatered to 20% solids using a three-step process: sedimentation, dissolved-air flotation, and centrifugation. The algal lipid is extracted with cellular disruption high-pressure homogenization followed by a hexane extraction process and is then sent to an upgrading facility to ultimately produce renewable diesel. The remaining lipid-extracted microalgae are sent to an anaerobic digester to produce biogas for power production and provide for nutrient recycling. The IAF scenario was run for 30 years using hourly-aggregated daily averages of biomass and lipid production, water use, and associated resource demands (see Figs. 2-3).

For this case study, we did not implement any operational window constraints, and dynamic pond harvesting is enabled when the culture

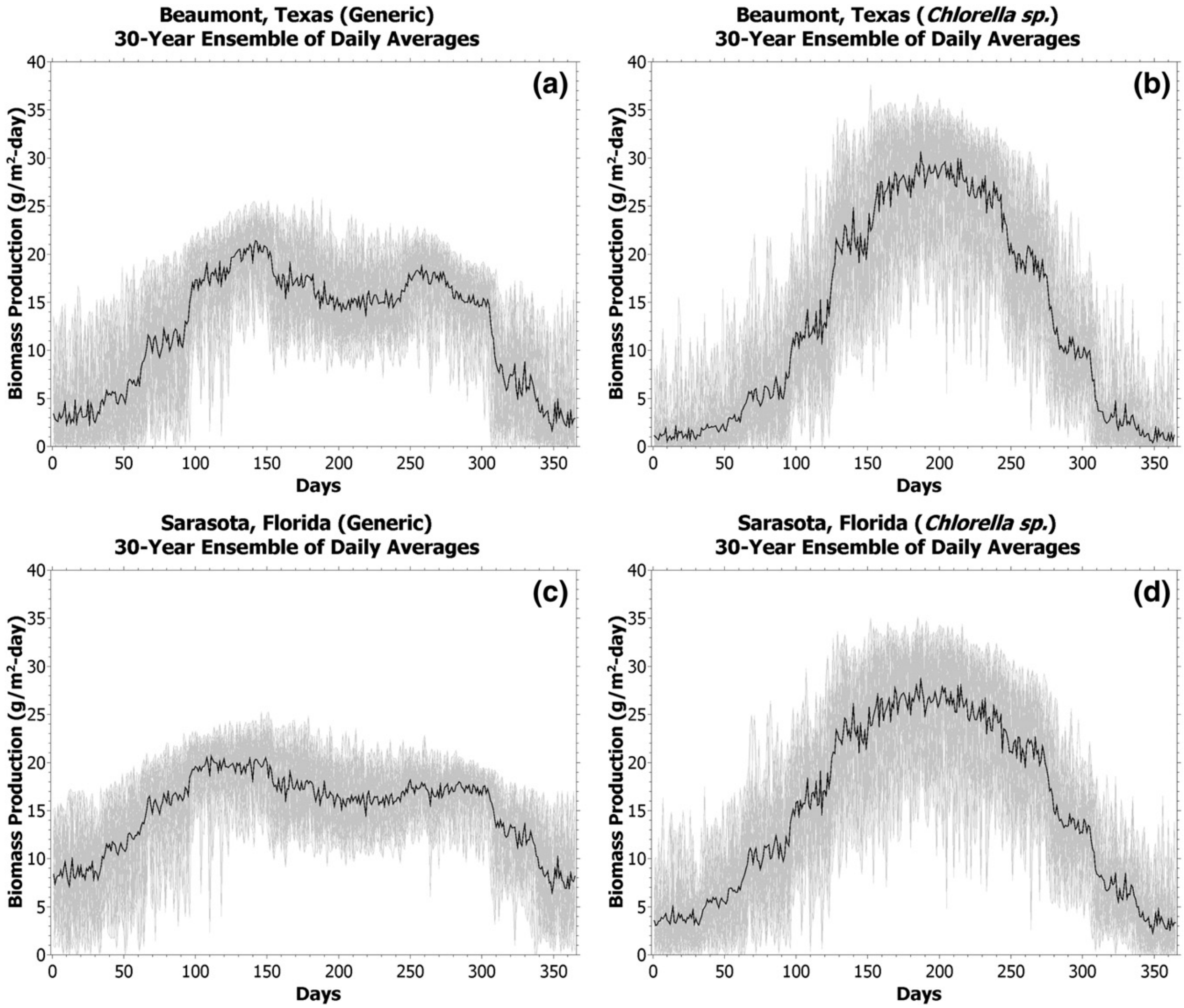

Fig. 6. Daily variability in biomass production over a 30-year period (gray) and long-term mean daily production (black) for two algal strains at two sites including (a) generic strain at Beaumont, Texas, (b) *Chlorella sp.* at Beaumont, Texas, (c) generic strain at Sarasota, Florida, and (d) *Chlorella sp.* at Sarasota, Florida.

density in a pond reaches 1.0 g/l, which was selected based on findings by Lynn et al. [50]. When the downstream processing equipment is being used at its full design capacity, the pond is taken offline and the culture is held until downstream processing capacity becomes available. This approach is implemented with the understanding that the pond needs to be harvested within 24 h before the culture density begins to decline [49]. Specific details of the resource assessment and techno-economic parameters used in this study can be found in ANL/NREL/PNNL [8], Wigmosta et al. [18], and Abodeely et al. [37–39].

4. Results

4.1. Baseline analysis comparison

Information about large-scale algal biofuel production systems is not prevalent in the literature and previous TEA/LCAs to this regard are limited as noted by Quinn et al. [51]. The design and analysis of the US DOE model harmonization study [8] build off of numerous key findings in past studies to bring about a model with explicit consideration for large-scale production systems. As such, this study was used as the benchmark for validating the IAF model. While it is not ideal to validate one model to another, observed data of this type are largely non-existent, proprietary or limited in their content. The IAF was compared against the ANL/NREL/PNNL [8] model-harmonized design by 1) assembling the technology modules within the ALM to be consistent with the harmonized baseline design described in the case study; 2) implementing the operational assumptions of the unit farm; and 3) applying the BAT-produced average algal biomass production and resource requirements for the specific site. This harmonization study did not evaluate individual sites, but rather divided the U.S. Gulf Coast region into eight clusters and assigned a long-term average annual and seasonal algal biomass production and resource requirement to each cluster. Fig. 4 shows the CapEx and OpEx breakdown for a site in Beaumont, Texas, which is contained in "Group 3" of the ANL/NREL/PNNL [8] clusters. Under the harmonized design, seasonal algal biomass production, and resource requirement assumptions, the IAF determined that the total cost of producing renewable diesel is \$20.71/gal, a difference of less than 1% of the results in the harmonization study when we use the same cluster boundaries and averages. While some of this cost difference is attributable to the method of CO_2 delivery (as noted in the case study description), a great deal of uncertainty undoubtedly exists in large-scale open-pond system design and is sensitive to assumptions in models [51]. Therefore, we believe that the cost difference in the baseline is acceptable. Additional details regarding the cost breakdown of each process are provided by Abodeely et al. [37–39].

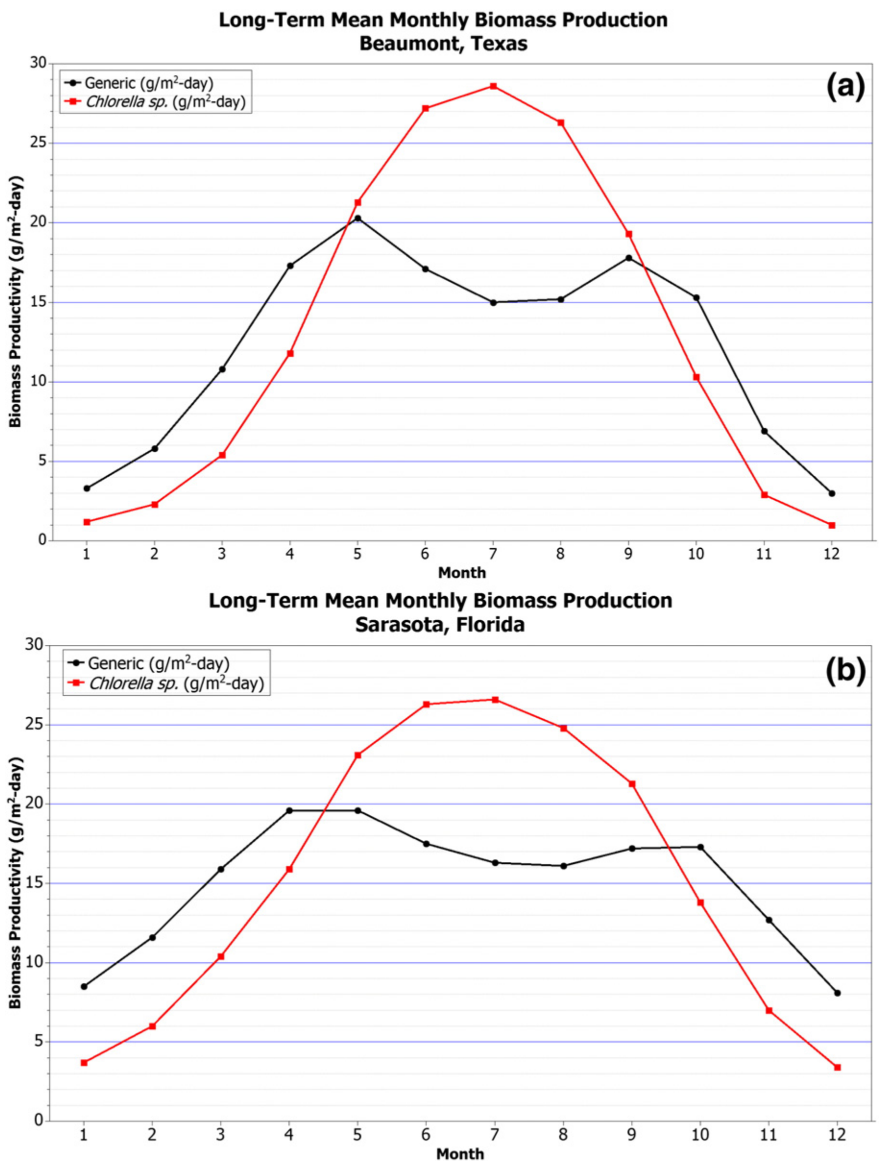

Fig. 7. Comparison of simulated 30-year average monthly biomass production (g/m^2-day) for two algal strains at Beaumont, Texas and Sarasota, Florida.

4.2. Design scaling

A major challenge to determining throughput design capacity for the algal feedstock processing system is the impact of feedstock production variability. Because the feedstock production system dominates the overall capital expense of the algal biofuel enterprise, designing the ideal processing capacity requires systematic exploration of the trade-offs between site-specific production potential and resource demand and availability.

A primary objective in design capacity scaling is to avoid the potential diseconomies of scale created by idle downstream processing equipment. If the post-cultivation processes are scaled to certain productivity levels, the excess biomass on the high-productivity days must be managed under an operational assumption, for example, the dynamic harvesting approach as described in the case study. The IAF can address the cost trade-offs between having ponds offline – when the rate of biomass production exceeds the operating capacity of the downstream equipment to process the biomass, resulting in less biomass production – versus having more capital investment in equipment to handle short-duration, high-magnitude periods of biomass production. Production duration curves are used to determine the likelihood of algal biomass rates of productivity based on long-term performance. By assessing the algal production systems at various scales based on the productivity potential of the site, the IAF can determine the ideal scale of the downstream processes to help minimize costs and uncertainty.

4.2.1. Effects of variability on production

Multiple dimensions of variability directly affect the most cost-effective design capacity of the microalgae processing system. Examples of such variability are illustrated by IAF simulation results in Figs. 5–8. Fine-scale temporal variability is shown in Fig. 5, where the day-to-day biomass productivity for a representative 1-year period is compared at two of the 5-BGY sites (Beaumont, Texas, and Sarasota, Florida) for two algal strains. This figure demonstrates the strong correlation between productivity and the integrated effect of short-term meteorological variability on algal production. Significant temporal variability in biomass productivity is also observed at an inter-annual scale.

Fig. 6 shows the daily production values for two locations and two strains over the continuum of 30 years as an ensemble of modeled values; the study period minimum and maximum biomass productions define the outer boundaries of the ensemble spread. This demonstrates the daily and annual variation in biomass productivity which is a

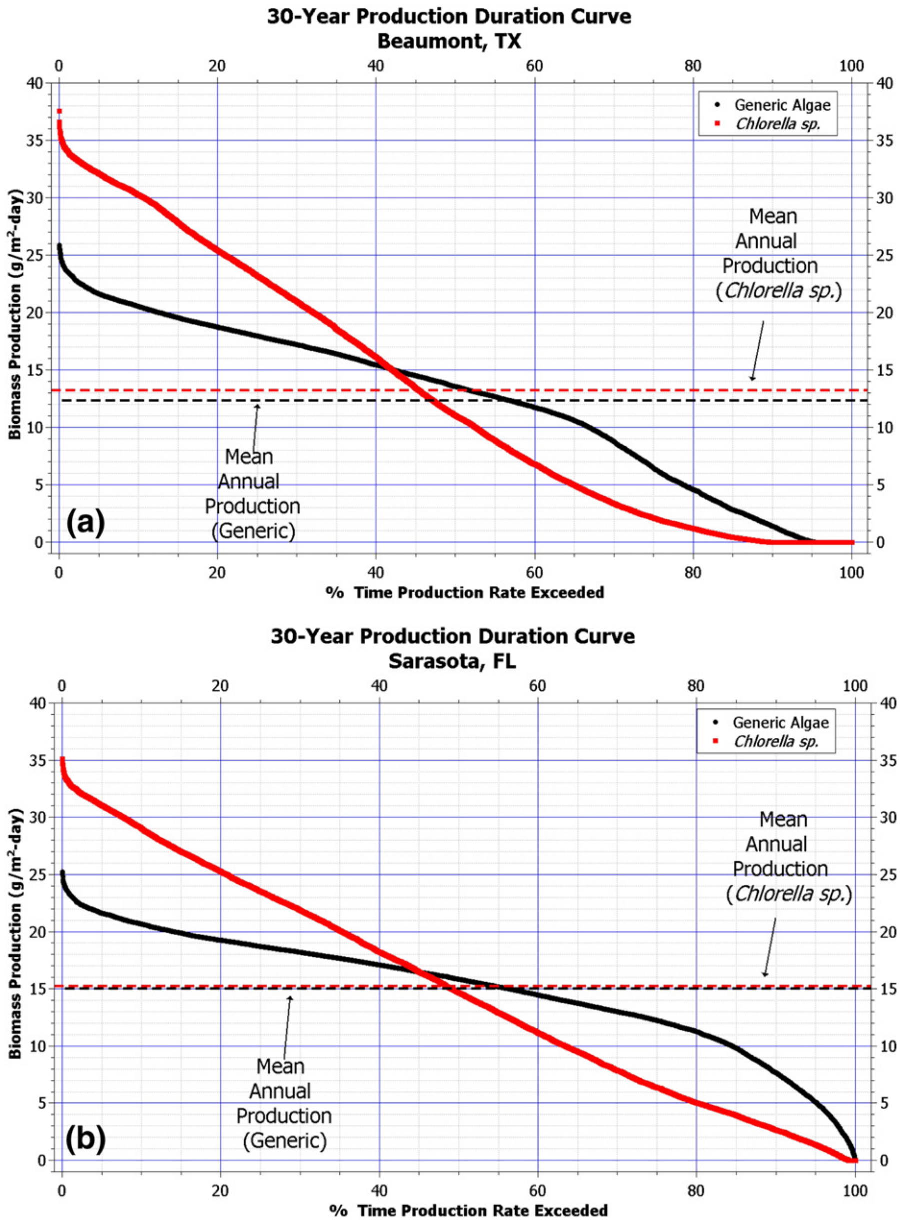

Fig. 8. 30-year production duration curves and corresponding long-term annual average values (dashed lines) for two algal strains at Beaumont, Texas, and Sarasota, Florida.

function of local variability in meteorology e.g., solar insolation, air temperature, precipitation, and relative humidity drive pond water temperature and light availability. For the two sites, the long-term mean daily productivity is approximately 8.4 g/m^2-day less than the maximum productivity for C*hlorella sp.* at Beaumont, 7.9 g/m^2-day less for C*hlorella sp.* at Sarasota, 6.8 g/m^2-day less for the generic strain at Beaumont, and 5.1 g/m^2-day less for the generic strain at Sarasota. For more information, Table 1 presents the long-term daily minimum, mean, maximum, standard deviation, and all time daily maximum for both sites and both strains.

Evaluation of the daily productivities over a 30-year period indicates a wide-range of inter-annual variability, which, again, is a result of meteorological variability and specific response by the algal strain. For example, evaluating the 30-year record at the Beaumont site, the total annual production variability can fluctuate as much as 70 K gallons in any given year, with costs fluctuating by $1.20 per gallon. This

Table 1
Long-term (30-years) production statistics for Beaumont, Texas and Sarasota, Florida for the generic and *Chlorella sp.* strains. All units are presented in g/m^2-day.

Location	Strain	Daily Min	Daily Mean	Daily Max	Daily SD	All Time Maximum Daily
Beaumont, TX						
	Generic	5.9	12.4	19.2	6.9	25.9
	Chlorella sp.	7.4	13.2	21.6	11.23	37.6
Sarasota, FL						
	Generic	8.21	15.0	20.1	4.9	25.3
	Chlorella sp.	6.7	15.3	23.2	9.7	35.1

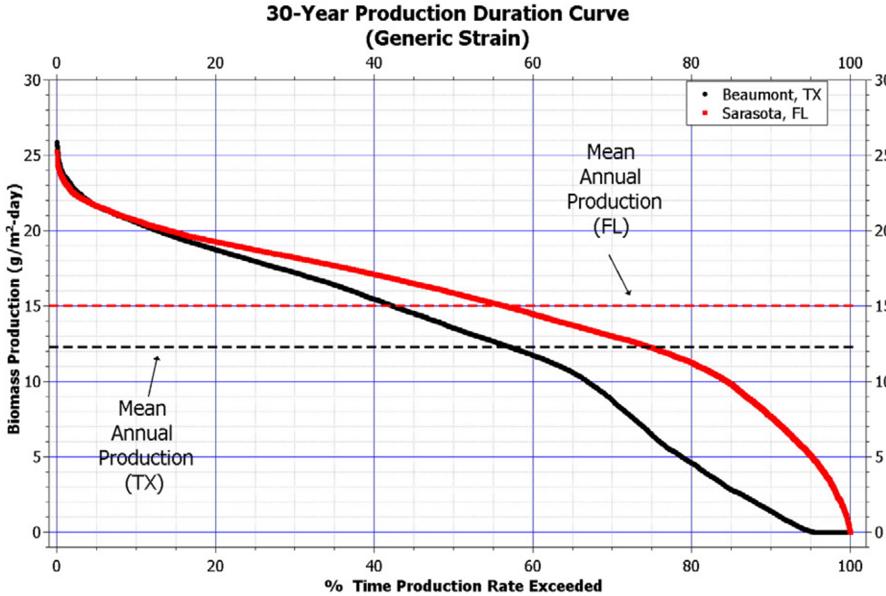

Fig. 9. Production duration curves using the ideal design capacity for a single strain at both Beaumont, Texas, and Sarasota, Florida.

emphasizes the need to evaluate temporal variability in production and not rely solely upon long-term mean annual production values when performing facility design. The cost fluctuation, while not abundantly large at this particular site, is caused by scaling to the maximum productivity threshold, which results in post-cultivation processing equipment remaining idle for long periods during the year or for an entire year depending on meteorological conditions. This increases the uncertainty of production and cost for the system.

Broadening the temporal scale, Fig. 7 shows the simulated 30-year long-term average monthly productivities for the same two sites and strains and demonstrates the sensitivity of alternative strains to extreme temperatures over longer periods. The productivities at both locations drop to less than 5 g/m^2-day during winter, revealing an intolerance for low temperatures. Productivity for the C*hlorella sp.* strain, which prefers high temperatures, follows a bell-shaped curve with maximum productivities in excess of 25 g/m^2-day during July. The simulated performance of the generic strain is representative of strains that have reduced productivity in more extreme pond water temperatures (in this case, above 30 °C).

Fig. 8 shows the productivity duration curves for the generic and *Chlorella sp.* strains for Beaumont, Texas, and Sarasota, Florida. The curves capture both the magnitude and duration of productivity over a 30-year period. In general, winter low temperatures are warmer in Sarasota than Beaumont, while the summer temperatures are comparable at both locations. In addition, the Sarasota site is approximately 3° latitude farther to the south than Beaumont, providing for more consistent growing days during the year. Consequently, approximately 75% of the time, productivity is higher in Sarasota than Beaumont, while the upper ends of the productivities are very similar.

4.2.2. Influence of design capacity on production cost

Based on the environmental conditions described above, a key consideration is the integrated impact of temporal and spatial variability on the overall algal biofuel production design capacity and costs. The literature often assumes the design basis for algal biofuel processing systems to be an average annual productivity, maximum productivity, or an estimated productivity [7,8,23,25,28].

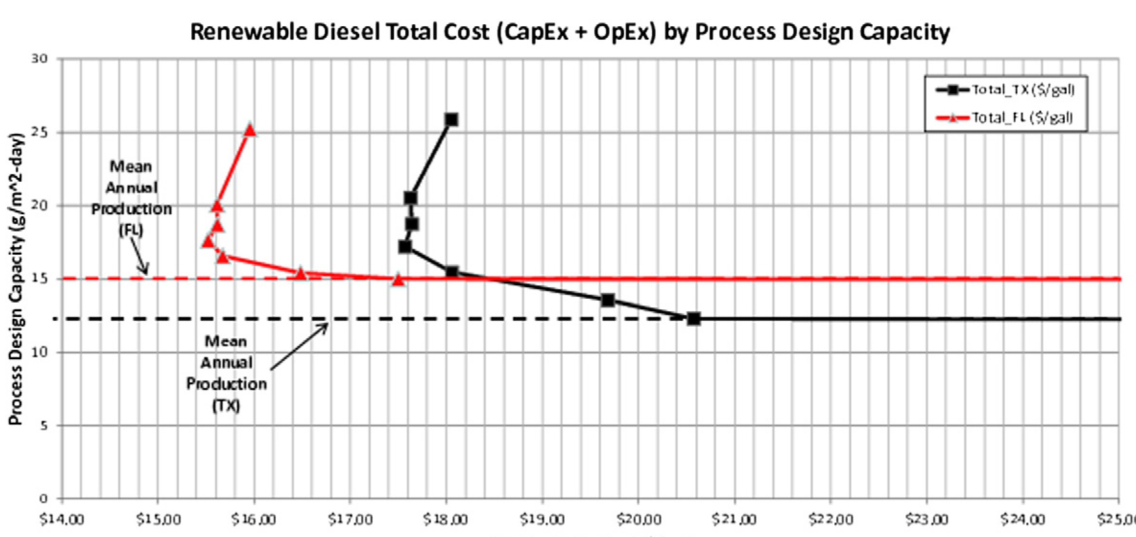

Fig. 10. Production cost curve showing total cost of renewable diesel (CapEx + OpEx) as a function of design capacity at Beaumont, Texas, and Sarasota, Florida.

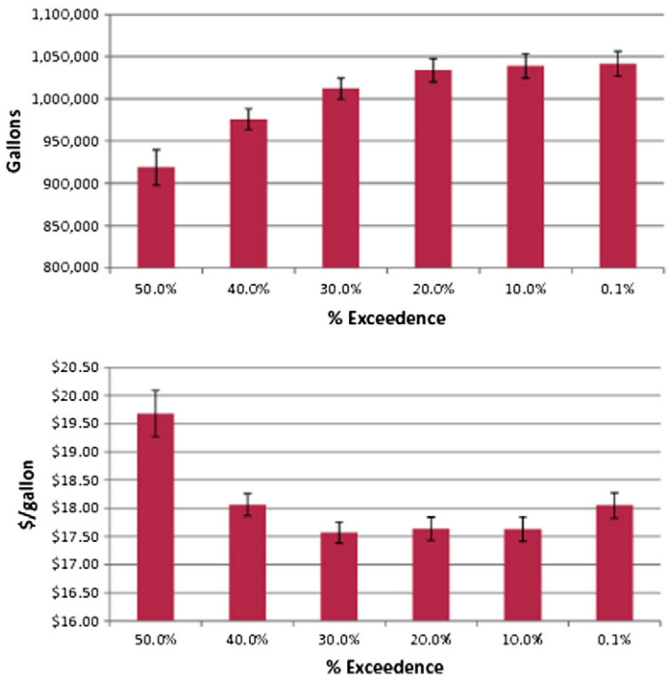

Fig. 11. IAF analysis captures renewable diesel production (top) and cost (bottom) and trade-offs at a range of design capacities for Beaumont, Texas.

To explore the reasonableness of such assumptions, we conducted an analysis within the case study wherein we developed design capacity vs. cost trade-off curves for two locations within the DOE model-harmonization study's 5-BGY sites, based on the IAF's generic algal strain model. The analysis investigated the impact of variability in a simulated 30-year production period on the ideal design capacity at the Beaumont and Sarasota sites (Fig. 9). As discussed previously, the climate at the Sarasota location has a higher algal biomass productivity approximately 70% of the time on average and a mean biomass production of 15 g/m^2-day compared to about 12 g/m^2-day at Beaumont. The peak rates of productivity are similar at both sites.

Fig. 10 shows the resultant design capacity (g/m^2-day) versus total cost trade-off curves (represented as the total cost to produce renewable diesel in \$/gal) for the two locations assuming the lipid extraction plus anaerobic digestion technology pathway, and assuming a fixed number of lined algal feedstock production ponds as determined by freshwater availability. A number of observations can be made from these curves. The ideal design capacity is observed at 17.2 g/m^2-day for Beaumont and 17.7 g/m^2-day for Sarasota using the generic microalgae. While these two sites have fairly similar production design capacities, it was observed in many cases around the study area, other sites nearby one another exhibit more variation in this regard. Nonetheless, the corresponding renewable diesel cost is more than \$2.00/gal less for the Sarasota site, reflecting in this case the benefit of the higher biomass productivity. The curves also show that when moving away from the optimum, overall, there is a greater increase in renewable diesel cost with decreasing design capacity than with increasing capacity. It is also observed that as capacity continues to decrease, a critical threshold is reached, and under our current operational assumptions for handling the excess biomass, the cost increases significantly. Given that pond liners represent a large percentage (~75%) of the CapEx costs, there is a cost advantage to designing the overall system to keep the ponds in production as much as possible, and there is minimal financial risk of overdesigning the downstream processing system. However, when considering the ideal design capacity, the least amount of variability is observed when downstream processing is scaled to around 30% exceedence for the Beaumont site with slight increases as the scale moves from 10% to 20% exceedence, which is where renewable diesel is produced at the lowest cost (Fig. 11).

4.2.3. *Influence of spatial location on ideal exceedence value*

The variability described above clearly demonstrates that production rates are highly dependent on site location, and therefore there is a need to be cautious in using average annual or maximum rates of production for optimum scaling of a facility. The analysis conducted using the IAF demonstrates the importance of scaling the downstream processing to achieve finer-scale economics of algal biofuel production. It also indicates that design scaling of algae farms is a non-linear process.

Tables 2 and 3 present the results for this exceedence-based cost analysis for the Beaumont and Sarasota sites, respectively. The tables show the CapEx and OpEx in total and as cost per gallon in 10% increments of exceedence, mean annual production, and maximum production value in the time-series. While not evaluated for this study, the resultant renewable diesel cost coming from a production facility with unlined open ponds is expected to be much more sensitive to the presented processing system design capacity and resultant CapEx/OpEx. This is due to recent findings that pond liners are the "single largest cost impact" to a production facility [8] and these costs would not vary over time and space outside of minimal differences in transportation cost.

The full set of 5-BGY sites was run through the IAF using the baseline design scenario at 10% exceedence intervals, the mean annual production, and maximum production value in the time-series, allowing analysis capability equal to that presented for the Beaumont and Sarasota sites. Analysis of the full set of 5-BGY sites reveals, for each site, the most cost-effective design capacity, derived from the lowest CapEx/OpEx cost per gallon (Fig. 12). The variability of ideal exceedence capacities ranges from 0.1% (maximum productivity) at a few limited sites in central Florida, to 30% extending along the Texas Gulf Coast, the Florida panhandle, northeastern Florida, and a pocket in central Florida. The regions exhibiting ideal designs at 20% exceedence dominate in southeast Florida, on the Atlantic Coast of north-central Florida, the Gulf Coast region of north Florida, and sites in the south Texas plains. Throughout more of interior Florida and the greater New Orleans area and southeast

Table 2
Results of exceedence-based cost analysis at 10% increments for Beaumont, Texas.

Design Level	Production Rate	% Time Exceeded	CapEx/gal	Total Capital Cost	OpEx/gal	Total Operational Cost	Total Cost/gal
90% Exceedence	1.4	90	\$13,342.68	\$47,157,263	\$4085.21	\$3,274,709	\$17,427.89
80% Exceedence	4.6	80	\$408.82	\$48,076,240	\$129.41	\$3,487,295	\$538.23
70% Exceedence	8.8	70	\$204.27	\$49,677,897	\$60.74	\$3,331,230	\$265.01
60% Exceedence	11.7	60	\$82.00	\$50,057,540	\$28.23	\$4,144,807	\$110.23
Average production	12.3	57.1	\$14.10	\$52,428,353	\$6.47	\$5,438,934	\$20.57
50% Exceedence	13.6	50	\$13.45	\$53,537,433	\$6.23	\$5,602,084	\$19.68
40% Exceedence	15.5	40	\$12.15	\$51,065,457	\$5.91	\$5,606,247	\$18.06
30% Exceedence	17.2	30	\$11.79	\$51,353,670	\$5.78	\$5,687,344	\$17.57
20% Exceedence	18.7	20	\$11.86	\$52,090,060	\$5.78	\$5,732,655	\$17.64
10% Exceedence	20.5	10	\$11.86	\$52,234,427	\$5.77	\$5,744,746	\$17.63
Max production	25.9	0.01	\$12.22	\$53,912,933	\$5.83	\$5,813,600	\$18.05

Table 3
Results of exceedence-based cost analysis at 10% increments for Sarasota, Florida.

Design Level	Production Rate	% Time Exceeded	CapEx/gal	Total Capital Cost	OpEx/gal	Total Operational Cost	Total Cost/gal
90% Exceedence	8.4	90	$129,792.86	$51,371,963	$38,319.38	$3,418,574	$168,112.25
80% Exceedence	11.5	80	$1,700.27	$51,147,913	$515.48	$3,560,250	$2,215.75
70% Exceedence	12.8	70	$656.94	$51,679,103	$201.78	$3,712,827	$858.72
60% Exceedence	14.0	60	$230.93	$52,465,790	$73.39	$4,134,490	$304.32
Average production	15.0	56.5	$11.78	$55,299,993	$5.72	$5,999,962	$17.50
50% Exceedence	15.4	50	$11.01	$55,646,847	$5.47	$6,174,657	$16.48
40% Exceedence	16.6	40	$10.37	$54,332,873	$5.31	$6,205,862	$15.67
30% Exceedence	17.7	30	$10.25	$54,439,223	$5.27	$6,240,930	$15.52
20% Exceedence	18.7	20	$10.34	$55,148,157	$5.28	$6,279,875	$15.62
10% Exceedence	20.1	10	$10.34	$55,267,463	$5.27	$6,289,610	$15.62
Max production	25.3	0.009	$10.64	$56,870,547	$5.32	$6,355,490	$15.96

region of Acadiana in Louisiana, 10% exceedence is the most common ideal design capacity. The sites in Florida and Louisiana showing a 0.1% or 10% exceedence generally indicate a more consistent and stable rate of biomass production throughout the year, whereas sites at the 30% exceedence value suggest a higher variability, which is driven by the meteorology and climate patterns over the 30-year period.

While the respective exceedence values reveal the most-effective design capacity for a given site, it is self-consistent and not necessarily reflective of the region in terms of identifying sites that produce renewable diesel at the least cost per gallon. Using an individual site's ideal design capacity, the associated total cost per gallon of renewable diesel is determined (Fig. 13). There is a higher degree of spatial diversity across the 5-BGY sites compared to the reasonably well-defined clusters of ideal exceedence capacity. While some of these spatial patterns may reveal themselves if the exceedence capacities are run at a finer increment than 10%, this analysis shows the diversity of costs not only between broad regions, but also among local sites, which are potentially affected by secondary factors such as the site's water and/or nutrient delivery costs, land acquisition cost, maintenance and insurance rates, etc.

To exercise the analysis capabilities of the IAF-produced data at the various exceedence thresholds, a comparison of cost per gallon between an individual site's maximum productivity over the 30-year time-series (0.1% exceedence) and the most cost-effective exceedence value was completed and is presented in Fig. 14. This analysis spans a cost-per-gallon difference of $0–$2 per gallon for the 5-BGY sites, with lower differences at the central and southern Florida locations and greatest differences at the Florida panhandle and Louisiana sites. While the cost difference is not largely significant in this particular design case, it does contribute to finer-scale cost efficiencies. In addition, identifying ideal design capacities will become increasingly important as larger cost barriers, such as pond liners, become more cost-effective or are replaced with a less-expensive technology solution.

5. Conclusions

The IAF is an analytical platform that enables comprehensive assessments of local, regional, and national microalgae production capabilities, feedstock logistics, and infrastructure. It has the flexibility to

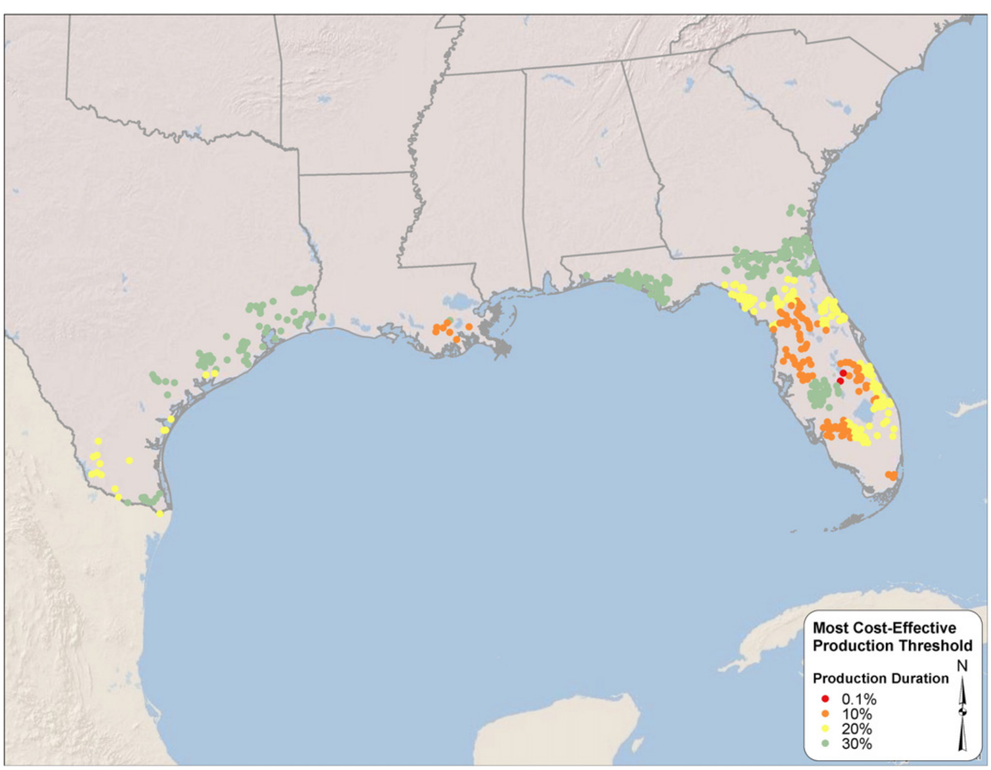

Fig. 12. The most cost-effective production duration threshold (exceedence capacity) determined by the lowest CapEx + OpEx costs per gallon of renewable diesel for each of the 5-BGY sites.

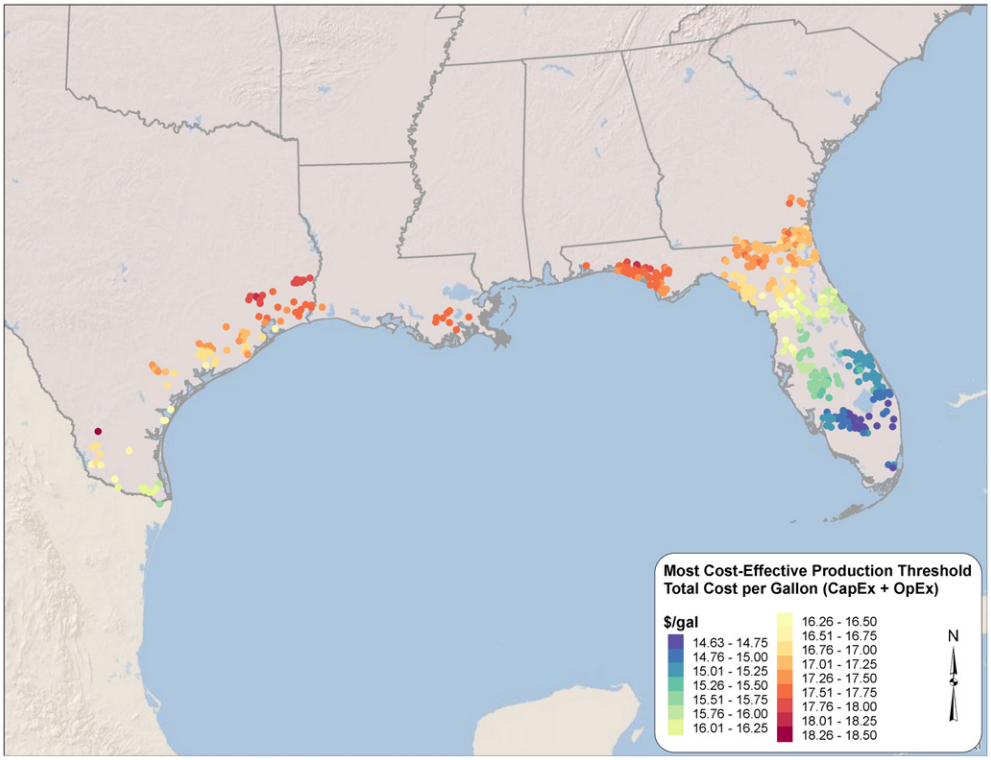

Fig. 13. The dollars per gallon of renewable diesel are shown for each of the 5-BGY sites using the most cost-effective design capacity for each site.

conduct analyses based on cost, energetics, and trade-offs between multiple pathways and algal strains using current and future technology designs in a spatially and temporally explicit manner. The IAF's resource assessment capabilities identify potential locations for microalgae feedstock production, resource demands, economics associated with acquiring and delivering required resources, and determining biomass production rates for a given site.

The production site logistics and costing within the IAF use a TEA-style approach and demonstrate a baseline supply system design for downstream processing and moving microalgae biomass into biomass

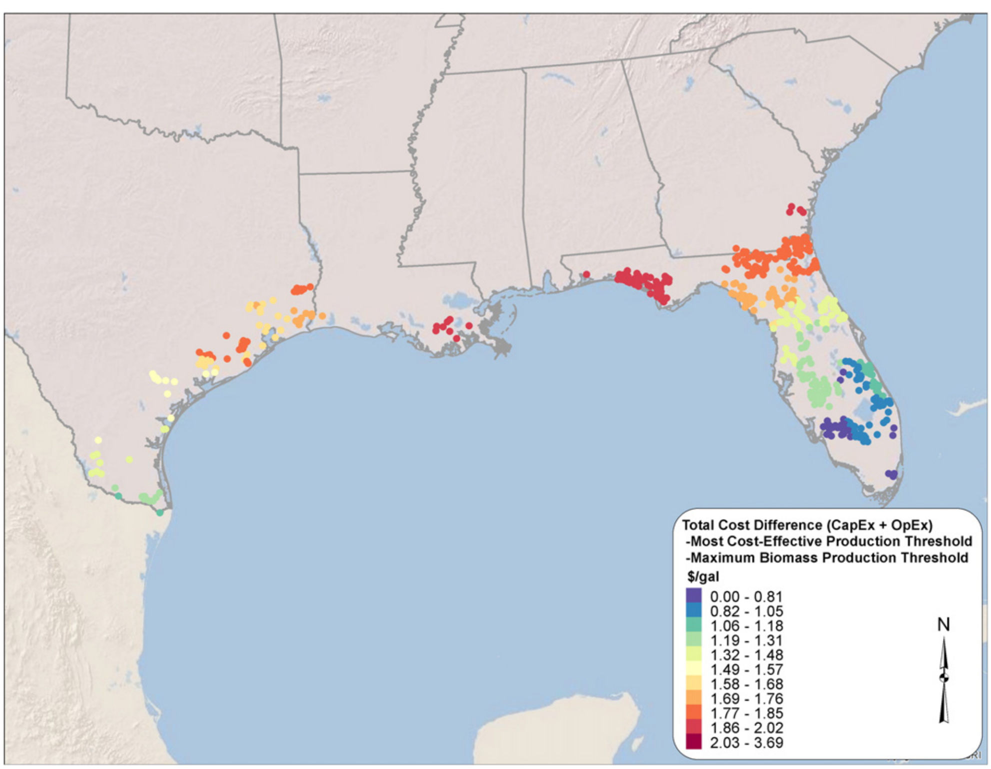

Fig. 14. The cost difference of renewable diesel in dollars per gallon when comparing the 5-BGY sites run at a rate of maximum production observed over a 30-year period and the most cost-effective design capacity.

feedstock supply systems for fuel upgrading. The spatiotemporal relationships are explicitly considered to identify ideal locations for production and operations from an economics perspective. The role of feedstock production variability as a function of place and operational design reveals important considerations related to production uncertainty and the importance of considering multi-temporal trends to inform an ideal scale for downstream processing capability. The nature of the production variability demonstrates that the effectiveness in using average annual or maximum rates of production for the design basis in TEA is highly site dependent.

Analyses of the design scaling are shown to be non-linear and are performed to determine current costs and identify the potential for reducing these costs through finer-scale system performance and economies of scale. The impetus for the design scaling was founded on the principle of the "production duration curve", providing a different approach to evaluate ideal capacity designs. The duration curve captures both the magnitude and duration of productivity, in the case of this study, over a 30-year period. Results from the cost production curves at the two demonstration sites suggest the financial risk of overdesigning downstream processing equipment is less than that of putting ponds in standby while waiting for production capacity to become available; however, this scenario may not be true everywhere.

Considering the full 5-BGY case study for sites in the southeastern U.S., there is variability in the ideal exceedence capacities ranging from 0.1% to 30%. The IAF analysis also shows that production costs can vary from site to site and aren't necessarily consistent throughout a region, indicating local meteorological differences, resource constraints, or secondary impacts associated with CapEx and OpEx. In the current case study design, the significant cost impact of pond liners on the CapEx overshadows some of the finer-scale economic benefits that can be realized by implementing a site-specific ideal design scale and provides the impetus for future scenario analyses.

Acknowledgements

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References

[1] International Energy Association (IEA), World energy outlook 2012, Accessed online 15 June 2013 http://www.worldenergyoutlook.org/ 2012.
[2] U.S. Energy Information Administration (EIA), International energy outlook 2011, Accessed online 15 June 2013 http://www.eia.gov/forecasts/ieo/transportation.cfm 2011.
[3] S. Chu, A. Majumdar, Opportunities and challenges for a sustainable energy future, Nature 488 (2012) 294–303, http://dx.doi.org/10.1038/nature11475.
[4] S.A. Scott, M.P. Davey, J.S. Dennis, I. Horst, C.J. Howe, D.J. Lea-Smith, A.G. Smith, Biodiesel from algae: challenges and prospects, Curr. Opin. Biotechnol. 21 (2010) 277–286.
[5] U.S. Department of Energy (DOE), National Algal Biofuels Technology Roadmap Bioenergy Technologies Office, Office of Energy Efficiency and Renewable Energy, Washington, D.C., 2010. (DOE/EE-0332, Available online, http://www1.eere.energy.gov/biomass/pdfs/algal_biofuels_roadmap.pdf).
[6] P.J.L.B. Williams, L.M.L. Laurens, Microalgae as biodiesel & biomass feedstocks: review & analysis of the biochemistry, energetics, & economics, Energy Environ. Sci. 3 (2010) 554–590.
[7] A. Sun, R. Davis, M. Starbuck, A. Ben-Amotz, R. Pate, P.T. Pienkos, Comparative cost analysis of algal oil production for biofuels, Energy 36 (2011) 5169–5179.
[8] ANL, NREL, PNNL. (June 2012). Renewable diesel from algal lipids: an integrated baseline for cost, emissions, and resource potential from a harmonized model. ANL/ESD/12-4; NREL/TP-5100-55431; PNNL-21437. Argonne, IL: Argonne National Laboratory; Golden, CO: National Renewable Energy Laboratory; Richland, WA: Pacific Northwest National Laboratory.
[9] E.R. Venteris, R. Skaggs, A.M. Coleman, M.S. Wigmosta, A GIS cost model to assess the availability of freshwater, seawater, and saline groundwater for algal biofuel production in the United States, Environ. Sci. Technol. 47 (9) (2013) 4840–4849, http://dx.doi.org/10.1021/es304135b.
[10] E.R. Venteris, R.L. Skaggs, M.S. Wigmosta, A.M. Coleman, A national-scale comparison of resource and nutrient demands for algae-based biofuel production by lipid extraction and hydrothermal liquefaction, Biomass Bioenergy 64 (2014) 276–290, http://dx.doi.org/10.1016/j.biombioe.2014.02.001.
[11] National Resource Council, Sustainable development of algal biofuels in the United States Washington, DC, The National Academies Press, 2012.
[12] E.L. Maxwell, A.G. Folder, Resource assessment for saline aquatic biomass production systems, Proceedings of the SERI biomass program principal investigators' review meeting — aquatic species program reports. Re. SERI/CP-231–1808Solar Energy Research Institute, Golden, CO, 1982, (Available online: http://www.nrel.gov/docs/legosti/old/1808.pdf).
[13] E.L. Maxwell, A.G. Folger, S.E. Hogg, Resource evaluation and site selection for microalgae production systems Re. SERI/TR-215–2484, Solar Energy Research Institute, Golden, CO, 1985.
[14] B.W. Vignon, M.F. Arthur, L.G. Taft, C.K. Wagner, E.S. Lipinsky, J.H. Litchfield, C.D. McCandlish, R. Clark, Resource assessment for microalgal emergent aquatic biomass systems in the arid southwest Re. 6660-0301(225), Battelle-Columbus Division, Columbus, OH for Solar Energy Research Institute, Golden, CO, 1982.
[15] J. Sheehan, T.J. Dunahay, J. Benemann, P. Roessler, A look back at the U.S. Dept. of Energy's Aquatic Species Program: biodiesel from algae Rep. TP-580-24190, Natl. Renewable Energy Lab, Golden, CO, 1998.
[16] T. Lundquist, T.C. Woertz, N.W.T. Quinn, J.R. Benemann, A realistic technology and engineering assessment of algae biofuel production, Energy Biosciences Institute, University of California, Berkeley, 2010. p. 178.
[17] R.C. Pate, G. Klise, B. Wu, Resource demand implications for US algae biofuels production scale-up, Appl. Energy 88 (2011) 3377–3388.
[18] M.S. Wigmosta, A.M. Coleman, R.J. Skaggs, M.H. Huesemann, L.J. Lane, National microalgae biofuel production potential and resource demand, Water Resour. Res. 47 (2011) W00H04.
[19] J.C. Quinn, K. Catton, N. Wagner, T.H. Bradley, Current large-scale US biofuel potential from microalgae cultivated in photobioreactors, Bioenergy Res. 5 (1) (2012) 49–60.
[20] E.R. Venteris, R.L. Skaggs, A.M. Coleman, M.S. Wigmosta, An assessment of land availability and price in the coterminous United States for conversion of algal biofuel production, Biomass Bioenergy 47 (2012) 483–497.
[21] R.C. Pate, Resource requirements for the large-scale production of algal biofuels, Biofuels 4 (4) (2013) 409–435.
[22] P.T. Pienkos, L. Laurens, A. Aden, Making biofuel from microalgae, Am. Sci. 99 (6) (2011), http://dx.doi.org/10.1511/2011/93.474.
[23] F. Delrue, Y. Li-Beisson, P.-A. Setier, C. Sahut, A. Roubaud, A.-K. Froment, G. Peltier, Comparison of various microalgae liquid biofuel production pathways based on energetic, economic and environmental criteria, Bioresour. Technol. 136 (2013) 205–212.
[24] L. Amer, B. Adhikari, J. Pellegrino, Technoeconomic analysis of five microalgae-to-biofuels processes of varying complexity, Bioresour. Technol. 102 (2011) 9350–9359.
[25] R. Davis, A. Aden, P.T. Pienkos, Techo-economic analysis of autotrophic microalgae for fuel production, Appl. Energy 88 (2011) 3524–3531.
[26] G. Pokoo-Aikins, A. Nadim, M.M. El-Halwagi, V. Mahalec, Design and analysis of biodiesel production from algae grown through carbon sequestration, Clean Techn. Environ. Policy 12 (2010) 239–254, http://dx.doi.org/10.1007/s10098-009-0215-6.
[27] E. Stephens, I.L. Ross, Z. King, J.H. Mussgnug, O. Kruse, C. Posten, M.A. Borowitzka, B. Hankamer, An economic and technical evaluation of microalgal biofuels, Nat. Biotechnol. 28 (2010) 126–128.
[28] S. Nagarajan, S.K. Chou, S. Cao, C. Wu, Z. Zhou, An updated comprehensive techo-economic analysis of algae biodiesel, Bioresour. Technol. 145 (2013) 150–156.
[29] J.W. Richardson, M.D. Johnson, J.L. Outlaw, Economic comparison of open pond raceways to photo bio-reactors for profitable production of algae for transportation fuels in the Southwest, Algal Res. 1 (2011) 93–100.
[30] F. Delrue, P.-A. Setier, C. Sahut, L. Cournac, A. Roubaud, G. Peltier, A.-K. Froment, An economic, sustainability, and energetic model of biodiesel production from microalgae, Bioresour. Technol. 111 (2012) 191–200.
[31] C.F. Fisher, S. Paik Jr., R. Schriver, Power plant economy of scale and cost trends — further analyses and review of empirical studies, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1986. (ORNL/Sub-85–7685/1–11, DE86–014410).
[32] J.E. Hibdon, M.J. Mueller, Economies of scale in petroleum refining, 1947–1984: a survivor principle–time series analysis, Rev. Ind. Organ. 5 (3) (1990) 25–43.
[33] M.H. Nguyen, R.G.H. Prince, Simple rule for bioenergy conversion plant size optimization: bioethanol from sugar cane and sweet sorghum, Biomass Bioenergy 10 (5–6) (1996) 361–365.
[34] B.M. Jenkins, A comment on the optimal sizing of a biomass utilization facility under constant and variable cost scaling, Biomass Bioenergy 13 (1997) 1–9.
[35] M. Wright, R.C. Brown, Establishing the optimal sizes of different kinds of biorefineries, Biofuels, Bioprod. Bioref. 1 (2007) 191–200.
[36] T.L. Richard, Challenges in scaling up biofuels infrastructure, Science 329 (2010) 793–796.
[37] J.M. Abodeely, A.M. Coleman, D.M. Stevens, A.E. Ray, K.G. Cafferty, D.T. Newby, Assessment of algal farm designs using a dynamic modular approach, Algal Res. 5 (2014) 264–273 (in this issue).
[38] J.M. Abodeely, Algae-based biofuels integrated assessment framework: development, evaluation, and demonstration, USDOE Bioenergy Technologies Office Project Peer Review, 2013. (Alexandria, VA. Available online: https://www2.eere.energy.gov/biomass/peer_review2013/Portal/Algae/).
[39] J.M. Abodeely, A.M. Coleman, R. Skaggs, D.M. Stevens, A.E. Ray, M.S. Wigmosta, D.T. Newby, Integrated assessment framework for evaluation of algal production systems, USDOE Biomass, Washington, D.C, 2013.

[40] K.G. Cafferty, D.J. Muth, J.J. Jacobson, K.M. Bryden, Model based biomass system design of feedstock supply systems for bioenergy production, ASME International Design Engineering Technical Conference & Computers and Information in Engineering ConferenceASME, Portland, OR, 2013.
[41] P. Spolaore, C. Joannis-Cassan, E. Duran, A. Isambert, Commercial applications of microalgae, J. Biosci. Bioeng. 101 (2) (2006) 87–96.
[42] R. Harun, M. Singh, G.M. Forde, M.K. Danquah, Bioprocess engineering of microalgae to produce a variety of consumer products, Renew. Sustain. Energy Rev. 14 (2010) 1037–1047.
[43] T.M. Mata, A.A. Martins, N.S. Caetano, Microalgae for biodiesel production and other applications: a review, Renew. Sustain. Energy Rev. 14 (2010) 217–232.
[44] I. Priyadarshani, B. Rath, Commercial and industrial applications of micro algae — a review, J. Algal Biomass Utln. 3 (4) (2012) 89–100.
[45] O. Jorquera, A. Kiperstok, E.A. Sales, M. Embirucu, M.L. Ghirardi, Comparative energy lifecycle analyses of microalgal biomass production in open ponds and photobioreactors, Bioresour. Technol. 101 (2010) 1406–1413.
[46] Sapphire Energy, Sapphire Energy's commercial demonstration algae-to-energy facility now operational, Available online http://www.sapphireenergy.com/press-article/1078792-sapphire-energy-s-commercial-demonstration-algae-to-energy-facility 2011.
[47] C.E. Canter, The sustainability of biofuels produced from microalgae, University of Arizona, Tucson, Arizona, 2013.
[48] H.A. Foster, Theoretical frequency curves and their application to engineering problems, Am. Soc. Civ. Eng. Trans. 87 (1924) 142–303.
[49] J.K. Searcy, Flow–duration curves, manual of hydrology: part 2, Low-flow techniques. U.S. Geological Survey Water-Supply Paper 1542-A, 1959.
[50] D.C. Lynn, L.A. Ogaard, W.L. Foster, G.L. Carrasco, C.M. Vasquez, R.D. Simmons, High frequency algal pond harvest demonstration: a proof-of-principal in culture viability under applied algal farm management and operations with methodology comparisons in the evaluation and prediction of crop productivity and yield, Center of Excellence for Hazardous Materials Management, Carlsbad, New Mexico, 2011.
[51] J. Quinn, L. Winter, T. Bradley, Microalgae bulk growth model with application to industrial scale systems, Bioresour. Technol. 102 (2011) 5083–5092.